

Soil moisture and salinity as main drivers of soil respiration across natural xeromorphic vegetation and agricultural lands in an arid desert region

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ABSTRACT

The conversion of extreme xeromorphic vegetation (natural desert forest) to agricultural lands is one of the largest land-use changes in the arid desert region of China over the past 30 years, which may substantially influence soil respiration, and hence may largely determine local climate change. However, few studies have considered the change in soil respiration across natural desert forest and agricultural lands in the arid desert region. In this study, soil respiration and its influencing factors, i.e., soil moisture content, soil salinity, microbial quantity, soil temperature, fine-root biomass, soil organic matter (SOM), air temperature, pH and relative air humidity, were determined across natural desert forest and three chronosequential fields where forests have been converted to agricultural lands having varying length of cultivation period (i.e., 5, 10 and 30 years of cultivation) in an arid desert region. We used two-way repeated measure ANOVA for evaluating significant differences in soil respiration and its influencing factors between natural desert forest and agricultural lands, and then employed structural equation model (SEM) with the support of stepwise regressions analyses to test for the direct and indirect effects of influencing factors on soil respiration. The results showed that soil respiration significantly increased along the years of cultivation in agricultural lands ($P < 0.05$). Soil respiration was higher in all agricultural lands than that in natural desert forest ($P < 0.05$). Stepwise regressions and SEM showed that soil moisture content and soil salinity had explained 75% of the variation in soil respiration through direct and indirect effects via abiotic and biotic factors. Soil respiration was significantly affected by the sum of the direct and indirect effects of soil salinity ($\beta = -0.46$) and soil moisture content ($\beta = 0.49$) via microbial quantity, soil temperature, fine-root biomass and SOM. This study suggests that deforestation and subsequent agricultural activities might alter the soil moisture and salinity contents, and as a consequence influence soil respiration across natural desert forest and agricultural lands in an arid desert region.

1. Introduction

Globally, annual carbon emissions to atmosphere due to soil respirations reach 75–120 Pg C (10^{15} g) (Hibbard et al., 2005; Raich and Schlesinger, 1992), which is almost equal to 11 times of carbon emissions from fossil fuels (Marland et al., 2009), and just fall below the gross primary productivity ($100\text{--}120$ Pg C yr^{-1}) (Musselman and Fox, 1991). Arid and semi-arid deserts account for approximately one-fourth of the global land surface (Polis, 1991). Recently, (semi-) arid deserts are recognized as the most sensitive ecosystems to the climate change, probably due to the increased rates of desertification and land-use change in recent decades (Mccartney and Zornberg, 2009; Mvk, 2007;

Schlesinger, 2016). Soil respiration is contributing much to the carbon emissions due to the influences of climate change on the edaphic conditions in the arid desert regions (Wang and Li, 2013; Zhang et al., 2008). However, the contribution of soil respiration to the regional or local climate change and its influencing or driving factors remains the subject of debate in arid desert regions.

Land-use change emissions account for about 50% of carbon emissions within a specific ecosystem (Hibbard et al., 2005; Raich and Schlesinger, 1992). Any type of land-use change would cause a significant differences in the soil respiration (Mahowald et al., 2016; Smith et al., 2016; Wiesmeier et al., 2014), vegetation cover, anthropogenic activities, and soil properties (Javed et al., 2008; Materechera and

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Mkhabela, 2001; Y. Zhang et al., 2015). The desert area of the Xinjiang Uygur Autonomous Region is covering more than half of the desert land in China, which plays important roles in both social and ecological aspects of the region. It is generally well-understood that arid desert area consisted of three landscape parts, i.e., oasis, desert-oasis ecotone and desert (Polis, 1991). Oasis is a small area in a desert that has a supply of water and is able to support vegetation and anthropogenic activities. Oppositely, desert is a barren area of the landscape where little precipitation occurs and consequently, living conditions are hostile for plant and agricultural activities, whereas desert-oasis ecotone is an interactive zone where interchange of energy and mass occurs between the desert and oasis ecosystems. The extreme xeromorphic vegetation (natural desert forest) grows primarily in desert-oasis ecotone in the arid desert areas. Although the large-scale deforestation in desert-oasis ecotone has rapidly expanded the area of an oasis in recent decades, natural forest of desert-oasis ecotone has continuously been decreased in Xinjiang Uygur Autonomous Region (Amuti and Luo, 2014; F. Zhang et al., 2015). The majority of natural desert forests were converted to agriculture lands. In this context, we anticipate that deforestation and the subsequent agricultural activities are the major causes for the changes in soil respiration, soil properties, and carbon balance of regional cycle in Xinjiang Uygur Autonomous Region (Amuti and Luo, 2014; Gong et al., 2015; Liu et al., 2016). Yet, our understandings of whether and how land reclamation affects soil respiration remain unclear.

Carbon emissions due to soil respiration arise mainly from the chemical oxidation of soil organic matter (SOM), fine-root and microbial respirations (Schlesinger and Andrews, 2000; Wiesmeier et al., 2014). It is also well understood that land-use change affects environmental factors and soil properties, which in turn may influence the chemical oxidation of SOM, fine-root and microbial respiration (Barton, 2013; Buchmann, 2000). Additionally, due to the contrast relationship in land-use change between agricultural lands and deforestation in arid desert region, new agricultural lands gradually replace natural desert forests along the edges of the oasis, which may cause gradual decrease in the years of cultivation in agricultural lands along with the distance to the oasis's center (Amuti and Luo, 2014; Walker, 1982). Here, the years of cultivation refers to the length of cultivation period after conversion of desert forest to agricultural lands (Bowman et al., 1990). Previous studies have suggested that some agricultural activities, i.e., soil tillage, irrigation, the interaction between soils and plants, can change environmental factors and soil properties along the years of cultivation (Bravogara and Bryan, 2005; Dalal and Mayer, 1986; Gong et al., 2015). In this case, we anticipate that the direct sources of soil respiration, i.e., the chemical oxidation of SOM, fine-root and microbial respiration, vary between natural desert forest and agricultural lands as well as with the years of cultivation of agricultural lands.

Soil temperature has been recognized as one of the major drivers for explaining variation in soil respiration along temporal-spatial scales in numerous studies (Karhu et al., 2014; Lloyd and Taylor, 1994; Thomson, 2010). However, the correlation between soil temperature and soil respiration is often not significant in the same period within a small area due to the homogeneity of land-surface radiation (Conant et al., 2000; Davidson et al., 2000; Wang et al., 2013). In contrast with the landscapes of desert and desert-oasis ecotone, agricultural lands at the periphery of the oasis account for only a small part of arid desert areas (Polis, 1991; F. Zhang et al., 2015). In addition, soil temperature has been proved to be not significantly different among agricultural lands in a given small-area of an oasis in arid desert regions due to the poor heat preservation of sandy soil and the same altitude position (Polis, 1991; see soil temperature data of He (2010)). However, soil moisture content and soil salinity have also been recognized as the main limiting factors for soil respiration in an arid desert region (Bui, 2013; Polis, 1991). Any small change in these factors could largely affect the chemical oxidation of SOM, fine-root and microbial respiration and their influencing environmental factors (Bui, 2013; Gong et al., 2015;

Noymeir, 1973; Sarig and Steinberger, 1994), as predicted by the law of the minimum limiting factor (Polis, 1991; Rubel, 2008). Thus, we anticipate that soil moisture content and soil salinity rather than soil temperature will affect soil respiration in arid desert regions. Moreover, it has also been reported that the soil temperatures induced by agricultural activities were not significantly different between natural desert forest and agricultural lands, as well as among the agricultural lands with the different years of cultivation at the same temporal scale (Han et al., 2017; Y. Zhang et al., 2015). However, agricultural activities can improve the distribution patterns of soil moisture and salinity (Gong et al., 2015), which in turn may affect the chemical oxidation of SOM, fine-root and microbial respiration (Gong et al., 2015; Han et al., 2017; Y. Zhang et al., 2015). Hence, it may be insightful to put forward the soil moisture and salinity as main drivers for explaining variations in soil respiration between natural desert forest and agricultural lands in arid desert region.

In this study, we aim to investigate the variation in soil respiration and its influencing or driving factors across natural forest and agricultural lands in an arid desert region in North-West China. Specifically, we addressed the following two major questions: 1) whether soil respiration varies between natural desert forest and agricultural lands, as well as among the agricultural lands with different years of cultivation; and 2) whether soil moisture and salinity cause any change in soil respiration via changes in abiotic and biotic factors across natural forest and agriculture lands in an arid desert region.

2. Materials and methods

2.1. Study site

The study was conducted in the Ebinur desert in the western edge of the Gurbantonggut desert in the Xinjiang Uygur Autonomous Region of western China (44°30'–45°09' N, 82°36'–83°50' E). The annual precipitation is < 50 mm whereas the evaporation exceeds 1600 mm, and the sunlight hours reach approximately 2800 h. Temperature ranges from –33 °C to 44 °C with average temperatures ranging from 6 °C to 8 °C. Due to the extremely dry conditions and the sparse rainfall, this region is characterized by a typical arid temperate climate. Owing to the northwest of this region is the well-known Alashankou tuyere zone, the prevailing wind direction in Ebinur desert is from the northwest. The annual average days of fresh gale up to 165 days, which is mostly concentrated from April to June. The soil belongs to Arenosols (AT) in the World Reference Base for Soil Resources, and the surface salt content ranges from 4 to 8% (Yang et al., 2014). The zonal vegetation is extreme xeromorphic vegetation, which is mainly composed of desert plants, where *Haloxylon ammodendron* and *Populus euphratica* are the important and dominant species (Yang et al., 2014). The maximum tree height of *Populus euphratica* and *Haloxylon ammodendron* is 15 m and 4.5 m, respectively. In addition to these species, some shrub and herbaceous species, such as *Alhagi sparsifolia*, *Nitraria tangutorum*, *Apocynum venetum*, *Salsola collina* and *Agriophyllum squarrosum*, are also occupying the region. The total vegetation coverage is < 10% (Yang et al., 2014).

In this study, the experimental plots were established in Tuotuo Town (44°33'–44°37'N, 83°33'–83°32'E), which is a piedmont alluvial oasis within the Ebinur desert. Over the past decade, many *Haloxylon ammodendron* and *Populus euphratica* dominated natural desert forests of desert-oasis ecotone in the surrounding of Tuotuo Town were converted into agricultural lands of oasis under the guidance of the strategy of “Western Development of China”. It is estimated that the oasis area of Tuotuo Town was enlarged > 4 times from 1984 to 2015 (Fig. 1). The predominant agricultural crops of the increasing agricultural lands of oasis are cotton and corn. In most years, the above two crops were cultivated in rotation with one crop grown at each year. All agricultural lands in this area used the cultivation techniques of the full-on treatment of flood irrigation, and the irrigation systems collectively

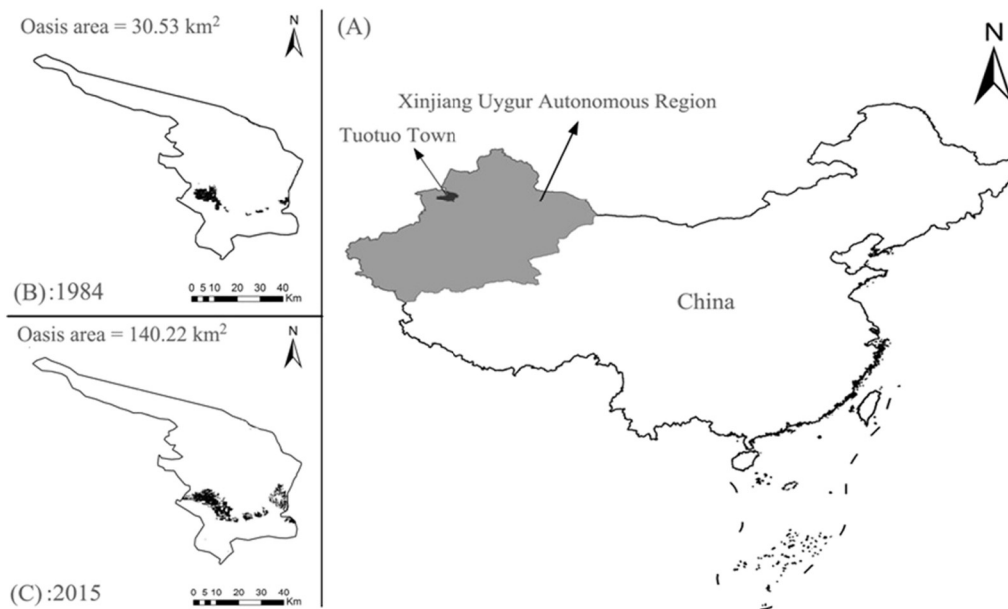


Fig. 1. Variation in oasis area of Tuotuo Town from 1984 to 2015. Tuotuo Town is the research area of this study, which is located in Ebinur desert region in the western margin of the Gurbantonggut desert in the Xinjiang Uygur Autonomous Region, NW China. For this study, the Landsat images of the year 1984 and 2015 are selected as the data source to extract the Oasis area. The process of area extraction and estimation was conducted in ArcGIS10.0 and ENVI4.8. Landsat images of the year 1984 and 2015 are obtained from United States Geological Survey.

managed by the local water authority. In order to increase yields, some chemical fertilizers, i.e. urea, diammonium phosphate and potassium sulphate, were mainly used by farmers to improve soil fertility during planting period of spring, and after that, the farmlands were no longer fertilized in the growing season. Since the fertilization was far away from the measurement time of soil respiration, the direct effects of fertilization on soil respiration were considered to be negligible. In addition, because the local farmers were the members of Xinjiang Production and Construction Corps (XPCC), agricultural activities such as tillage practices, soil disturbances, were uniform between the different agricultural lands with the different years of cultivation. The direct effects of agricultural activities on soil respiration were also neglected in this study. The XPCC is a unique economic and paramilitary organization in the Xinjiang Uygur Autonomous Region of China. The XPCC has administrative authority over several medium-sized cities as well as settlements and farms in Xinjiang.

2.2. Experimental design and measurements

Based on the official documents from the soil administrative department of the local government and validation through remote sensing data (Fig. 1), 12 experimental plots (having each size of 10 m × 10 m) were established equally across four types of lands based on the years of cultivation, i.e., natural desert forest, 3, 16 and 30 years, along the distance to the center of the oasis. Natural desert forest has not been cultivated (0 years of cultivation) and covered by *Haloxyylon ammodendron* and *Populus euphratica* species.

It is reported that the growing seasons of crops in Ebinur desert lasted from April to November (Sun et al., 2012). Among the many stages of growing seasons of crops, June and September are the third and the sixth months of the growing seasons, and hence are the bud and fruit stages for corn and cotton in the north of Xinjiang Uygur Autonomous Region, respectively (Huang and Li, 2017). It is a common concept that bud and fruit stages are the most important time periods of crops along growing seasons in agronomy (Huang and Li, 2017). Thus, in this study, soil respiration and its influencing environmental factors were measured in June and September.

The soil respiration rate was measured using an automatic soil CO₂ flux system (LI-8100, LI-COR Inc., Lincoln, USA). Three collars, which were comprised of PVC tubes with inner diameters of 20 cm and heights of 25 cm, were randomly established in each plot. Each collar was inserted 20 cm into the soils, leaving a top portion that protruded 5 cm

above ground level. Soil respiration was measured for two consecutive sunny days with the recording interval of 2 h at each observational period. In order to protect the measuring chamber of the automatic soil CO₂ flux system, the bigger stone and the larger uncorrupted branches of the soil surface in collar were cleared and then allowed to equilibrate for at least 24 h before the first measurement. The determination of the soil respiration rate included both biological (e.g., microbial, root, and faunal respirations) and non-biological (e.g., chemical oxidation) processes. Concurrently, the soil temperature at 10 cm depth adjacent to each PVC collar was measured using a thermocouple probe, which was attached to an LI-8100 system. The soil moisture at 5 cm, expressed as volumetric water content (VWC %), was measured directly by using an LI-8100 through an Echo type EC-10 soil water sensing probe (Decagon Devices, Inc., Pullman, WA). In addition, the air temperature and the relative air humidity at 150 cm above the ground were measured at each measurement times by using a hand held Kestrel weather and wind speed meter (4000, Nielsen-Kellerman, Boothwyn, PA, USA).

In each plot, three soil samples (0–10 cm depth) were respective collected in the vicinity of the collars using soil sampling tools (301.66, AMS, Inc., CA, USA) for the determination of fine root biomass (diameter ≤ 2 mm), pH, soil organic matter (SOM), soil salinity and microbial quantity. The inner diameter of soil cores was 2.50 cm.

A wet sieve method was used to separate fine roots from other organic material. Based on the degree of cohesion between cortex and periderm, color and tissue resilience, living roots and dead root were hand-separated. Living roots ≤ 2 mm in diameter were selected and over dried at 80 °C for 48 h. Then fine root biomass was calculated as dry weight and sampling area (i.e., mathematically as: (dry weight × 10⁶)/[π × D²/4]; g m⁻²; D was the inner diameter of soil cores). Soil salinity and pH were measured respectively by using a conductivity meter (DDS-12A, Hongyi, Inc., Shanghai, China) and a pH meter (PHS-3c, Leici, Inc., Shanghai, China), and SOM content using the oil bath-K₂CrO₄ titration method (Nelson and Sommers, 1974).

With respect to the biological properties of the soils (i.e. microbial quantity), culture media for the isolation of bacteria, actinomycetes, and fungi were nutrient agar plates, Gao medium, and Rose Bengal medium, respectively. Briefly, approximately 10 g of fresh soil was weighed into a conical flask, to which 100 mL of sterile water was added. The soil samples oscillated for 10 min to obtain a 10⁻¹ soil suspension. Simultaneously, 10–11 g of a soil sample was dried to calculate the moisture percentage. The suspension was diluted to 10⁻³ (fungi), 10⁻⁴ (actinomycetes), and 10⁻⁵ (bacteria), respectively.

Subsequently, 0.1 mL of the suspension was plated on the surface of culture medium via a pipette and a sterile glass rod. All plates were incubated while inverted at 28 °C for microbial growth. Bacteria and fungi counts were conducted after five days, while actinomycetes were tallied after seven days. The sum of the counts of each separate group was the total microbial quantity. The above method for the determination of microbial quantity followed by Vieira and Nahas (2005) and Pelczar et al. (2003).

All the above measurements for soil properties were repeated 3 times at each soil sample in each plot. Since irrigation has substantial influences on soil respiration and its influencing factors, in this study, each experimental time was conducted on the 10th day after irrigation. Therefore, the effects of irrigation on soil respiration and its influencing factors were ignored.

2.3. Statistical analyses

We used a two-way repeated measure analysis of variance (ANOVA) to test for the differences in soil respiration and its influencing environmental factors between natural desert forest and agricultural lands, as well as among the agricultural lands with different years of cultivation. Growth time (i.e. three and six months) and the years of cultivation (0, 3, 16 and 30 yrs) were two factors. Within the process of two-way repeated measure ANOVA, growth time and the years of cultivation were set as within-subject and between-subject factors, respectively. In *post-hoc* tests, if the variance of soil respiration and environmental factors was homogeneous among the years of cultivation, we then used least-squares mean separation with Duncan's correction to test the differences among the years of cultivation. Alternatively, if the variance was heterogeneous, we then used Tamhane's T2 test to evaluate the differences.

Structural equation model (SEM) can be used in two main ways. The one way is the confirmatory method, which is based on using a priori knowledge and hypotheses in the conceptual model (Ali et al., 2016). The other way is the exploratory method, which evaluates the different combinations of variables (including exogenous, mediators and endogenous) for the selection of best-fit model (van der Sande et al., 2017). The first method for SEM is mostly helpful for testing the theoretical views, whereas the second method is used to explore the exact unknown relationships among variables (van der Sande et al., 2017). In this study, we use a partially confirmatory SEM because the conceptual model structure is fixed as we know that some abiotic and biotic factors can explain soil respiration but we have several predictor variables, i.e., soil salinity, soil moisture content, SOM, soil temperature, microbial quantity and fine-root biomass. After that, SEM of exploratory method was used to test for the direct and indirect effects of environmental, biotic and abiotic factors on soil respiration. Since the explanatory variables in SEM include independent and intermediate variables, stepwise regressions analyses and the complementary bivariate relationships were used to pre-select the best independent and intermediate variables for further analyses in SEM. Specifically, the independent variables in the final optimal model of stepwise regressions analyses were selected as the exogenous variables whereas others variables (which were not retained in the final optimal model) were treated as mediator variables for explaining variation in soil respiration (see Table S1). In addition, the logical paths of SEM can also be decided by the complementary bivariate relationships and Pearson's correlations (Ali et al., 2016). In particular, if the results of the complementary bivariate relationships show there is no significant connection between soil respiration and environmental factors, as well as between exogenous and mediator variable, the unrelated logical paths can be removed from SEM. Remarkably, unlike the previous studies of soil respiration in non-salinization areas without regarding the relationship between soil salinity and soil temperature, our study assumed that soil salinity has a negative relationship with soil temperature based on the theory of temperature effects on salt migration in arid desert regions

(Ren et al., 2017). In the areas with higher groundwater levels, such as the agricultural lands of arid desert regions, a higher temperature will increase the rate of salt diffusion, and then reduce the salt concentration on the soil surface.

For the selection of the best-fit SEM, four tests were used to assess the model fit of all tested SEMs (Malaeb et al., 2000), i.e., the Chi-square (χ^2) test, standardized root mean square residual (SRMR), comparative fit index (CFI) and Akaike information criterion (AIC). Indicators for a best model fit to the data included non-significant ($P > 0.05$) χ^2 test statistic, CFI > 0.90 and SRMR < 0.08 (Browne and Cudeck, 1992). The indirect effect of a predictor was calculated by multiplying the standardized effects of all paths on one route, from one predictor to mediator and then to soil respiration rate, while the total effect was calculated by adding standardized direct and indirect effects (Ali et al., 2016; Grace, 2016). Given a lot of parameters were involved, SEM reliability was relevant to the amount of data (Ali et al., 2016; Grace, 2016). In this study, in order to increase the amount of data, SEM analyses were based on all recording data rather than the mean values of the three repetitive plots per 2 h over two consecutive days for each type of lands based on the years of cultivation. Specifically, the collar was set as the foothold of data analysis, and then the values of experimental indexes (i.e. fine root biomass, pH, SOM, soil salinity and microbial quantity) were assigned to a matrix that constructed by observed data (i.e. soil respiration rate, temperature and moisture). In this study, because the observed data in each collar of three repetitive plots were measured per 2 h over two consecutive days for each type of lands, the SEM analyses matrix included 3456 recording points (i.e. 2 stages of growing seasons \times 4 length of the years of cultivation \times three repetitive plots \times three repetitive collars \times two consecutive days \times 12 recording points in two consecutive days = 1728 data points). The complementary bivariate relationships to the SEM are provided in Table S2. The SEM was implemented using the *lavaan* package (Rosseel et al., 2012). All statistical analyses were conducted in R 3.4.2 (R Development Core Team, 2017).

3. Results

3.1. Differences in soil respiration and its influencing factors between natural desert forest and agricultural lands

The result of two-way repeated measure ANOVA showed that the soil respiration rate was significantly increased across the years of cultivation, and that soil respiration rate in all agricultural lands was higher as compared to natural desert forest ($P < 0.01$). Growth time and the years of cultivation had a significant interaction effect on soil respiration rate ($P < 0.01$) (Fig. 2). The effects of the years of cultivation on abiotic and biotic factors were not the same for all the variables. Specifically, SOM and soil moisture content increased significantly after 30 years of cultivation, whereas pH only increased significantly after 30 years, soil salinity decreased consistently across the years of cultivation, microbial quantity and fine-root biomass increased similarly in cultivated soils independently of the period of cultivation. Air temperature, relative air humidity and soil temperature did not differ significantly across the years of cultivation. Soil moisture content, microbial quantity, fine-root biomass and soil salinity were also interactively affected by growth time and the years of cultivation ($P < 0.01$), whereas SOM and pH were not interactively affected ($P > 0.05$) (Table 1).

3.2. Direct and indirect effects of soil moisture and salinity on soil respiration

The multi-model comparative approach, using stepwise regressions analyses, showed that soil salinity and soil moisture content were the main drivers for explaining variation in soil respiration ($R^2 = 0.82$, $P < 0.001$, AIC = -32.25 ; Table S1). This indicated that soil salinity

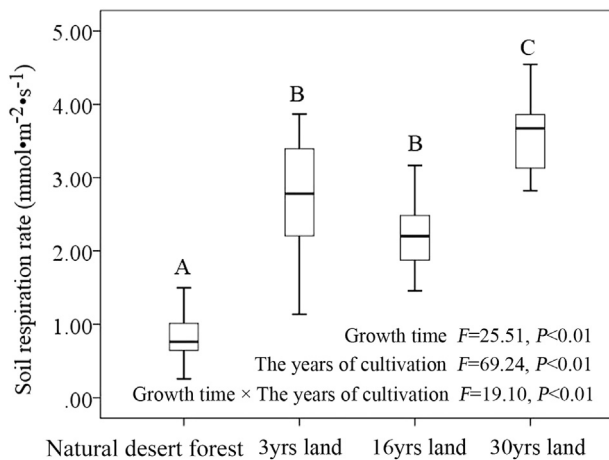


Fig. 2. Differences in soil respiration rate ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) between natural desert forest and agricultural lands, as well as among the agricultural lands with different years of cultivation in an arid desert region. Different uppercase letters in the horizontal direction on each plot-box indicate the significant differences in soil respiration rate among the different years of cultivation in agricultural lands, whereas the same uppercase letters show the non-significant differences. F -values and p -values are the results of two-way repeated measure ANOVA for the variability of soil respiration interactively induced by growth time and the years of cultivation. Values are shown as *Mean* \pm *SE*.

and soil moisture content could be included as the main exogenous variables whereas other environmental factors could be treated as the mediator variables in SEM. Since there were the insignificant relationships of air temperature to soil salinity and soil moisture content,

Table 2

The direct, indirect, and total standardized effects on soil respiration rate based on a best-fit structural equation model (SEM). The indirect effect was calculated by multiplying the standardized effects of all paths on one route, from one predictor (exogenous variables) to mediator, and then to soil respiration rate, while the total effect was calculated by adding standardized direct and indirect effects, presented in Fig. 3.

Predictor	Pathway to soil respiration rate	Effects	P-value
Soil moisture content	Direct effect	0.43	< 0.01
	Indirect effect via microbial quantity	0.07	0.04
	Indirect effect via soil temperature	−0.12	< 0.01
	Indirect effect via fine-root biomass	0.04	0.05
	Indirect effect via soil organic matter	0.07	< 0.01
	Total effect	0.49	< 0.05
Soil salinity	Direct effect	−0.28	< 0.01
	Indirect effect via microbial quantity	−0.18	< 0.01
	Indirect effect via soil temperature	0.07	0.07
	Indirect effect via fine-root biomass	−0.06	< 0.01
	Indirect effect via soil organic matter	−0.01	0.11
	Total effect	−0.46	< 0.01

as well as of soil respiration to the years of cultivation, growth time and relative air humidity in the complementary bivariate relationships, the logical paths of the above corresponding relation were removed from SEM (Table S2). The SEM having lowest AIC value was selected as the final best-fit SEM (Table 2), which yielded a reasonable outcome for explaining variation (i.e. 75%) in soil respiration rate through soil salinity and soil moisture content ($\chi^2 = 11.32$, $df = 4$, P -value = 0.07, CFI = 0.98, SRMR = 0.08 and AIC = 91.32) (Table 2; Fig. 3).

The best fit SEM showed that the soil salinity had a significant negative direct effect whereas soil moisture content had a significant

Table 1

Differences in abiotic and biotic factors between natural xeromorphic vegetation (desert forest) and agricultural lands, as well as among the agricultural lands with different years of cultivation in an arid desert region. Abiotic and biotic factors include soil salinity ($\text{g}\cdot\text{kg}^{-1}$), soil moisture content (volumetric water contents; %), soil organic matter (SOM; $\text{g}\cdot\text{kg}^{-1}$), soil temperature ($^{\circ}\text{C}$), microbial quantity ($\times 10^2$ CFU/g fresh soil), fine-root biomass ($\text{g}\cdot\text{m}^{-2}$), pH, relative air humidity (%) and air temperature ($^{\circ}\text{C}$). Values are shown as *Mean* \pm *SE*.

Environmental factors	The years of cultivation in agricultural lands (yrs)				Factors	df	F-value	P-value
	Natural desert forest	3	16	30				
Soil salinity	29.05 \pm 12.27A	12.08 \pm 4.88B	4.21 \pm 2.20C	3.86 \pm 1.09C	Growth time	1	14.51	< 0.01
Soil moisture content	8.34 \pm 1.11A	9.47 \pm 1.38A	18.48 \pm 1.79B	18.36 \pm 1.20B	The years of cultivation	3	11.04	< 0.01
					Growth time \times The years of cultivation	3	11.13	< 0.01
					Growth time	1	20.59	< 0.01
					The years of cultivation	3	128.46	< 0.01
SOM	16.77 \pm 8.34A	16.22 \pm 3.03A	14.30 \pm 2.57A	26.99 \pm 6.07B	Growth time \times The years of cultivation	3	6.66	< 0.01
					Growth time	1	0.05	0.83
					The years of cultivation	3	5.19	< 0.05
					Growth time \times The years of cultivation	3	0.06	0.98
pH	8.51 \pm 0.10A	8.19 \pm 0.08A	8.43 \pm 0.21A	8.03 \pm 0.04B	Growth time	1	0.35	0.56
					The years of cultivation	3	24.11	< 0.01
					Growth time \times The years of cultivation	3	1.44	0.28
					Growth time	1	15.22	< 0.01
Relative air humidity	31.22 \pm 14.99A	26.51 \pm 11.27A	31.00 \pm 18.40A	37.35 \pm 14.41A	The years of cultivation	3	0.50	0.68
					Growth time \times The years of cultivation	3	1.85	0.19
					Growth time	1	24.52	< 0.01
					The years of cultivation	3	0.36	0.78
Air temperature	26.00 \pm 6.75A	28.33 \pm 7.29A	28.39 \pm 7.04A	25.00 \pm 4.02A	Growth time \times The years of cultivation	3	4.84	0.05
					Growth time	1	1068.42	< 0.01
					The years of cultivation	3	3.45	0.05
					Growth time \times The years of cultivation	3	56.82	< 0.01
Soil temperature	21.30 \pm 6.51A	19.64 \pm 2.69A	19.16 \pm 6.24A	17.33 \pm 4.50A	Growth time	1	9.59	< 0.01
					The years of cultivation	3	528.72	< 0.01
					Growth time \times The years of cultivation	3	70.65	< 0.01
					Growth time	1	58.91	< 0.01
Microbial quantity	89.10 \pm 16.24A	311.42 \pm 71.76B	315.73 \pm 29.85B	347.13 \pm 90.57B	The years of cultivation	3	9.83	< 0.01
					Growth time \times The years of cultivation	3	17.13	< 0.01
					Growth time	1	58.91	< 0.01
					The years of cultivation	3	9.83	< 0.01
Fine-root biomass	17.59 \pm 8.61A	38.85 \pm 20.78B	46.06 \pm 22.35B	51.80 \pm 26.27B	Growth time \times The years of cultivation	3	17.13	< 0.01
					Growth time	1	58.91	< 0.01
					The years of cultivation	3	9.83	< 0.01
					Growth time \times The years of cultivation	3	17.13	< 0.01

Note: Different uppercase letters in the horizontal direction after each value indicate the significant differences in the corresponding variables among the different years of cultivation of agricultural lands, whereas the same uppercase letters show the non-significant differences. F -values and p -values are the results of two-way repeated measure ANOVA for the variability of factors interactively induced by growth time and the length of cultivation period.

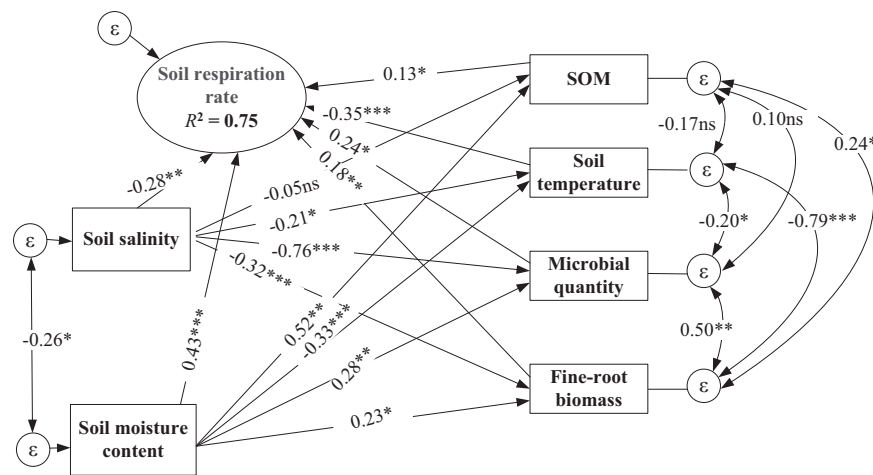


Fig. 3. Best-fit structural equation model (SEM) for soil respiration rate ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). Soil salinity ($\text{g}\cdot\text{kg}^{-1}$) and soil moisture content (volumetric water contents; %) were used as exogenous variables to explain the variation in soil respiration rate by testing direct and indirect effects through four mediator variables across natural desert forest and three chronosequential fields where forest has been converted to agricultural lands for varying length of time (5, 10 and 30 years of cultivation) in the arid desert region. Mediator variables include soil organic matter (SOM; $\text{g}\cdot\text{kg}^{-1}$), soil temperature ($^{\circ}\text{C}$), microbial quantity ($\times 10^2 \text{ CFU/g}$ fresh soil) and fine-root biomass ($\text{g}\cdot\text{m}^{-2}$). Value near to one-sided arrow represents regression coefficients whereas value near to double-sided arrow represents covariance between variables (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$; ns, non-significant). The coefficient of determination (R^2) represents explained variation in response variable by all exogenous and mediator variables. Epsilons (ϵ) within small circles represent the error term for downstream variables, ellipses represent response variable (soil respiration rate), and rectangles represent predictor variables.

positive direct effect on soil respiration rate (Fig. 3). As such, soil respiration was indirectly driven by soil salinity and moisture content via other abiotic and biotic factors (Table 2). Considering the total (direct + indirect) effects of soil salinity, soil respiration was negatively affected by the sum of the direct and indirect effects of soil salinity via fine-root biomass, soil temperature, microbial quantity and SOM (Fig. 3; Table 2). Soil respiration rate was positively affected by the sum of the direct and indirect effects of soil moisture content via soil temperature, SOM, microbial quantity and fine-root biomass (Fig. 3; Table 2).

In addition, SEM showed that soil salinity had the significant negative direct effects on soil temperature, microbial quantity and fine-root biomass, but not on SOM. Soil moisture content had significant positive direct effects on SOM, microbial quantity and fine-root biomass, but a negative effect on soil temperature. After accounting for the effects of soil salinity and moisture, soil respiration was significant directly affected by SOM, microbial quantity, fine-root biomass and soil temperature (Fig. 3).

4. Discussion

4.1. Soil respiration differs between natural desert forest and agricultural lands

In this study, within a short-term measurement, our results showed that soil respiration in agricultural lands was significantly higher as compared to natural desert forest, suggesting that deforestation and agricultural activities increased soil respiration across natural forest and agricultural lands in an arid desert region (Fig. 2). This result is in contrast with the previous numerous studies which suggested that soil respiration decreases after the conversion of natural forest to agricultural lands at the same latitudinal humid regions (Larionova et al., 1998; Smith et al., 2016; Wang et al., 2007; Y. Zhang et al., 2015). This might be resulted due to the differences in soil physicochemical properties and carbon storage between humid and arid desert regions. Compared to the humid ecosystem, the low soil moisture and SOM contents but high soil salinity are the most prominent characteristics of the arid desert ecosystem (Bui, 2013; Noymer, 1973; Polis, 1991). Within the process of the conversion of natural desert forest to agricultural lands, tillage, fertilization, irrigation, and the interactive relationships between crop and soils are advantageous to increase the levels of soil moisture and SOM contents and to decrease the soil salinity in the arid desert regions (Table 1) (Gong et al., 2015; Olsen et al., 1996). In this case, the improvements in these soil properties may, in

turn, enlarge the quantities of fine-roots biomass and microbes, and subsequently may increase soil respiration (Tables 1 and S2) (Conant et al., 2000; Gong et al., 2015; Liu et al., 2016; Paustian et al., 2010; Sarig and Steinberger, 1994). Oppositely, with respect to humid regions, SOM, the quantities of fine-roots biomass and microbes in natural forest are much better than those in agricultural lands (Larionova et al., 1998; Smith et al., 2016; Wang et al., 2007; Y. Zhang et al., 2015), in addition the loss of soil carbon in agricultural lands is higher than that in natural forest (Davidson and Ackerman, 1993; Gong et al., 2015; Materechera and Mkhabela, 2001; Wiesmeier et al., 2014). These subsequently resulted in dramatically shrinking of soil respiration after the conversion of natural forest to agricultural lands in humid regions (Barton, 2013; Buchmann, 2000; Schlesinger and Andrews, 2000; Wiesmeier et al., 2014).

In this study, our result showed that soil respiration increased along the years of cultivation in agricultural lands (Fig. 2), indicating that agricultural activities improved soil respiration in arid desert regions. This result is also in contrast with the previous studies of humid areas that soil respiration decreases across the years of cultivation in agricultural lands (Carmi et al., 2019; Javed et al., 2008; Smith et al., 2016; Tubiello et al., 2015). This distinction between both areas is possible because of the differences in SOM and physicochemical properties (Dalal and Mayer, 1986; Tubiello et al., 2015; Gong et al., 2015). In humid areas, due to the high soil fertility in natural forest rather than that in agricultural lands, the delivery in soil fertility results in early agricultural lands owning good soil rather than late. In addition, the long-term agricultural activities have negative effects on SOM and soil physicochemical properties due to soil erosion and nutrient loss (Bravogara and Bryan, 2005; Dalal and Mayer, 1986; Gong et al., 2015). In these case, soil respiration decreases across the years of cultivation in agricultural lands (Carmi et al., 2019; Javed et al., 2008; Smith et al., 2016; Tubiello et al., 2015). However, low SOM and poor soil physicochemical properties are the most important features of the arid desert regions (Bui, 2013; Polis, 1991). Thus, the long-term agricultural activities, i.e. irrigation, fertilization and tillage, are advantageous to improve SOM and physicochemical properties through the changes in water, nutrition, salinity, soil aggregate and natural soil conditions (Table 1) (Gong et al., 2015; Olsen et al., 1996), and hence, as a result, increased the fine-roots biomass and microbial quantities (Table 1). These subsequently resulted in the improvement of soil respiration along the years of cultivation in agricultural lands (Davidson and Ackerman, 1993; Gong et al., 2015; Materechera and Mkhabela, 2001; Wiesmeier et al., 2014). These were strongly observed in our analysis that soil moisture content, microbial quantity, fine-root

biomass, pH, soil temperature, SOM and soil salinity were significantly affected by the years of cultivation (Table 1).

4.2. Soil moisture and salinity as main drivers of soil respiration across natural desert forest and agricultural lands

As the main limiting factors of an arid desert ecosystem (Bui, 2013; Polis, 1991), any improvement of water will cause changes in the environmental factors and ecological processes of the desert ecosystem (Yang et al., 2017). In this study, we found that soil moisture was one of the major factors for explaining the large proportion of the variation in soil respiration (Fig. 3 and Table 2). This result indicating that soil moisture caused the variation in soil respiration between natural desert forest and agricultural lands, as well as among agricultural lands having the different years of cultivation in the arid desert region. This is due to the agricultural activities which gradually improve soil granular structure and increase the content of water-stable aggregates, and in turn improve the ability of water permeability and conservation (Gong et al., 2015; Han et al., 2017; Y. Zhang et al., 2015). Due to the improvement in soil moisture, SOM, soil permeability, plant root and microbial activities were also accordingly improved within the process of agricultural activities (Table 1) (Davidson et al., 2000; Linn and Doran, 1984; Orchard and Cook, 1983). These subsequently changes the substrate availability of soil respiration, particularly in SOM, resulting in the improvement of the chemical oxidation of the substrate, fine-root and microbial respiration (Table 1). Hence, the good changes in soil moisture improve soil respiration from natural forest to agricultural lands and along the years of cultivation in agricultural lands in the arid desert region. Additionally, it has been reported that soil moisture was positively related with microbial quantity, SOM and fine root biomass, whereas negative related with the fluctuation of soil temperature (Orchard and Cook, 1983; Polis, 1991; Wang et al., 2013). The effects of soil moisture on soil respiration also reflect the indirect benefits via the improvement in above mentioned underlying factors. Besides, soil moisture is highly dynamic due to the fact that sandy soils have very low water availability in arid desert regions. Our results of 10 days after irrigation showed soil moisture contents significantly differed among the years of cultivation. This is probably because the increase in SOM contributes to increasing water retentivity in agricultural lands of arid desert region. In this study, we observed strongly that soil moisture had the significant relationships with microbial quantity, soil temperature, SOM and fine root biomass (Table S2) ($P < 0.05$), and hence soil respiration rate was significantly affected by the indirect effects of soil moisture content via soil temperature, SOM, microbial quantity, and fine-root biomass (Fig. 2).

Soil salinity is another limiting environmental factor, which represents that groundwater is raised by capillary action to the surface of the soil in an arid desert region (Bui, 2013; Wang and Li, 2013). The reduction in soil salinity also causes the changes in the environmental factors and ecological processes of the desert ecosystem (Bui, 2013; Olsen et al., 1996). Our SEM result showed that soil respiration was direct negatively affected by soil salinity, which might be happened due to the agricultural activities and the improvements in soil moisture from natural desert forest to agricultural lands (Fig. 2) (Gong et al., 2015; Olsen et al., 1996). It is not surprising that soil penetrability and soil aggregate are improved due to agricultural activities along the years of cultivation (Gong et al., 2015; Jia et al., 2004). These improvements, in turn, are advantageous to strengthen the capability of soil eluviation, and then to decrease soil salinity along the years of cultivation (Gong et al., 2015). Owing to the negative stress of soil salinity to membranes system, biochemical metabolism, and the absorption of nutrients (Bui, 2013; Olsen et al., 1996), the reduction in soil salinity increases soil respiration along the years of cultivation in the arid desert region. We also found, in SEM, that the effects of soil salinity on soil respiration were reflected in indirect significant benefit by the reduction in fine-root biomass and microbial quantity, but not

via soil temperature and SOM (Fig. 2) ($P > 0.05$). This might be resulted due to the effects of soil salinity on carbon emissions of the biotic processes, but not of the abiotic (Bui, 2013; Wang and Li, 2013).

5. Conclusions and perspectives

This study demonstrates that soil respiration increases significantly along the years of cultivation in agricultural lands, and that soil respiration rate is higher as compared with natural desert forest. Variation in soil respiration is largely determined by soil moisture and soil salinity in an arid desert ecosystem. This study indicates that agricultural activities may improve the conditions of water and soil salinity after deforestation, and thereby increase soil respiration across natural forest and agricultural lands in an arid desert region. It is well-known that deforestation and subsequent agricultural activities are one of the major causes of climate change (Smith et al., 2016; Wiesmeier et al., 2014). The conversion of natural forest to agricultural lands may accelerate the carbon emissions due to the improvement in soil respiration rates and the reduction in SOM (Mahowald et al., 2016; Paustian et al., 2010; Raich and Schlesinger, 1992). In this study, our results show an obvious opposite result with the humid regions where SOM and soil respiration decrease from natural forest to agricultural lands (Wiesmeier et al., 2014; Mahowald et al., 2016; Smith et al., 2016). These results suggest that the improvement in SOM from natural forest to agricultural land is advantageous to store more carbon into soils that may decrease the carbon emissions. On the other sides, the improvement in soil respiration rates means a higher turnover rate in the agricultural soil which leads to higher efflux rates of CO_2 . These two conflicting processes may lead to the contrasting results in local carbon balance in arid desert regions. Thus, the previous theoretical knowledge that deforestation and subsequent agricultural activities accelerated climate change was not applicable in arid desert regions. However, it was difficult to estimate the devotion of balance between carbon capture and emission during a short-term measurement, which is one of the limitations of this study. Additionally, our study only chose to monitor soil respiration at the bud and fruit development stages of the crop, thus giving only some snap-shots of CO_2 emission from the experimental plots. The current results are relatively limited explanation of the variation in soil respiration over the entire crop growth period. Therefore, whether carbon balance and CO_2 emission from the agricultural lands in a long-term and over the entire crop growth periods are both similar with a short snap-shot of CO_2 emission are needed further researches. We anticipate that our research might encourage and inspire further long-term studies regarding soil respiration and its influencing factors across natural desert forest and agricultural lands in the arid desert regions. This study may be helpful to better understand the carbon balance of an arid desert ecosystem and to formulate the management strategies in answering climate change.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.catena.2019.02.015>.

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